Chapter 1
Introduction: James Watt's Social Network

Abstract We introduce ideas from network and graph theory and apply them to the evolution and network of contributions of the steam engine. Also discussed are models of growth of social networks, exponential growth and the 'S' curve. This chapter also reviews earlier work on evolution, diffusion and networks of innovation.

Did James Watt invent the steam engine? Did the Wright Brothers invent the airplane? In this book we examine the interactions between the genius-inventor and his or her social network using new ideas centered on modern networking systems. We also present evidence that invention is not just a moment of epiphany in a lone genius inventor, but is a culmination of an evolutionary process resulting from a network of people and institutions. In this spirit, our focus is primarily on the innovation network per se and not on the specific personalities for which there are many books and references. In this endeavor we take an experimental point of view by using the data from the historical record to explore models for innovation and invention.

Modeling innovation history using scientific constructs to uncover universal patterns has precedents in related fields such as biophysics and bioengineering. Many human systems such as epidemiology, traffic flow dynamics and demographics are the subject of mathematical modeling. Why not use network theory to uncover patterns in creative activities such as invention and innovation?

In the last two decades new information technologies have enabled millions of people to engage in social networking on a scale that was unimagined decades earlier. A byproduct of the growth of the World Wide Web, Facebook and Twitter has been a set of research studies on social networks resulting in popular books by Watts (2003), Barabasi (2003) and others. These studies suggest that we are in a new age of human communication and social dynamics that can stimulate innovation as well as trigger political change in places such as the Middle East and Asia through the use of social networking technology. Such claims prompt one to ask if communication networks played a role in earlier human activities in innovation and invention.

This author was first inspired to explore the role of networks in early theories of machine design beginning with the age of Leonardo da Vinci and spanning the industrial revolution in the nineteenth century (Moon 2007). A second study examined social networking in early aviation; did the Wright really invent heavier-than-air aircraft? (Moon 2012) The results of these earlier studies led the author to examine

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other technical and scientific innovations such as maritime clocks, internal combustion engines, early radio and more recently chaos theory.

Using models to understand the history of innovation has roots in Everett Rogers' *Diffusion of Innovation*, first published in 1962 and lately reissued. More recently there have been several books that describe the application of complexity theory to the study of history e.g. Mark Buchanan's *Ubiquity* (Buchanan 2000). Buchanan describes a new model called *self-organized criticality* or SOC to encompass several complex phenomena such as earthquakes and the growth of cities. Some of these theories focus on the propagation of consumer products into the marketplace made popular in a contemporary book *The Tipping Point,* by Gladwell (2000). Understanding market diffusion of new products and how they stimulate other products, as in the case of Apple's iPhone and the thousands of so-called 'Apps', is important. But the broader question is how the basic scientific and technical ideas behind these products evolved. In this book we focus on the early creative processes and the networks that produced these new ideas and products.

Beginning in the 1950s, physicist and historian of science Derek de Solla Price of Yale, brought mathematical methods to the sociology of science (1951). He showed that the growth of research publications of the past century followed an exponential function, doubling in 10–15 years. In another work, de Solla Price (1965a, b) studied the network of scientists by analyzing the citations they made of each others research papers. De Solla Price used statistical techniques to measure the productivity of scientists. In this book we seek a more detailed analysis of technical innovation by following the networks of individual contributors. We hope to provide some evidence for the statistical patterns of scientific and technical history through the action of the growth of networks.

Using graphics to encapsulate events and historical patterns has a long history as illustrated in the recent book *Cartographies of Time; A History of the Timeline*, by Rosenberg and Grafton (2010). They trace the use of chronologies in history to the Greeks and later to the fifth century CE. At the time of the steam engine, the British scientist, Joseph Preistley, a friend of Benjamin Franklin, published a *Chart of Biography* in 1765 with names of historical figures and dates of birth. We use event timetables in our monograph to search for exponential growth in several examples of innovation and invention.

A more recent example of using networks in historical studies is Randall Collins' *The Sociology of Philosophies* (1998) in which he analyzes the great philosophical traditions from the Greeks to the Chinese using graphical networks to trace the influence of philosophers across generations. He calls his work a history of intellectual networks and makes a case for the proposition that innovative ideas are found in groups and not in the isolated thinker.

Recently young historians, many from Germany and Austria, have formed an on-line network for the study of "Historical Network Research". [http://www.historicalnetworkanalysis.org] Areas of research include applications of network analysis to archeology, history of guild systems in the Holy Roman Empire, history of the Byzantine empire [see Preiser-Kapellier in the Bibliography], sociology of science and more. A broader organization is INSNA: International Network for

Social Network Analysis. Increasingly historians are using computer and quantitative methods to address questions in history and this monograph is hopefully a positive contribution to the use of networks in history of science and technology.

1.1 The Genius Theory of Innovation

As a society we are reluctant to ascribe all human behavior to the constraints of mathematical laws. We still revel in the myth of human geniuses: Archimedes, Newton, Madame Curie, Edison, Einstein and the Wright brothers. More recently we have elevated the late Steven Jobs of Apple into this pantheon. Stories of genius, trial and perseverance inspire and thrill us, especially the young and impressionable, in the vicarious process of human creativity,. However entrenched the genius-hero model of innovation is in modern society, there has long been recognition among historians of science and technology of the evolutionary nature of invention as well as the social connectedness of scientific and engineering achievement. For example the historian Usher (1929) write about the history of machines;

"*The more serious recent literature on the theory of invention theory recognizes the necessity of presenting invention as a cumulative synthesis of a relatively large number of individual items*."

In the nineteenth century, Thurston (1878) in a history of the steam engine argued,

"*Great Inventions are never, and great discoveries are seldom the work of any one mind*."

Perhaps inspired by the emergence of the *Theory of Evolution*, nineteenth century historians began to imagine that invention was also part of such a process, though on a shorter time scale.

A modification of the genius theory of innovation incorporates an evolution of scientific and technical ideas through the vehicle of successive genius-inventors. This idea is sometimes captured by the phrase '*on the shoulders of giants"* and was the title of a popular book. This theory is represented in Fig. 1.1 where ideas of human-powered flight begin with Leonardo and progress to the Wright Brothers without acknowledging the contributions of dozens if not hundreds of others. A more complete picture is presented in Chap. 4.

In physics we can draw a similar evolutionary genius chart beginning with Galileo and Newton in classical physics and ending with J. Clerk Maxwell and Einstein and Special Relativity, neglecting many major and minor contributors and institutions such as the Royal Society of London or parallel French and German scientific societies. In Chap. 6 of this book we trace the genius theories of nonlinear dynamics of chaos that became popular in the 1980s and use network analysis to illustrate the complexities of scientific progress.

Our plan for this book is to take historical evidence and construct network diagrams for eight different technologies and related sciences. We will also use historical data to plot innovation growth curves to seek evidence for innovation avalanches.

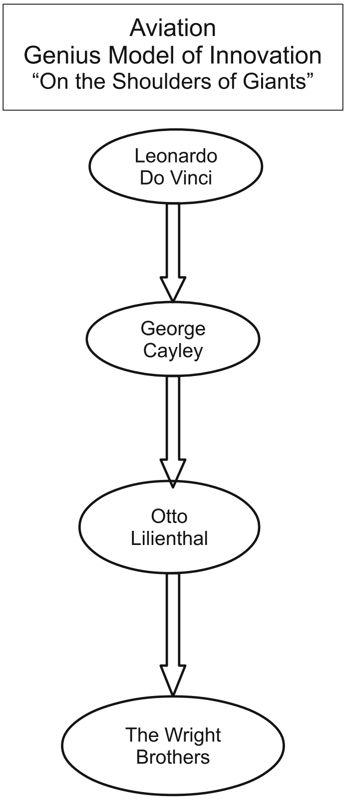

Fig. 1.1 An evolution chart for the genius theory of aviation

It is our premise that the exponential growth in technical innovation is linked to the growth of innovation networks.

1.1.1 Goal of this Monograph

The goal of this monograph is to provide further evidence to challenge the 'Genius Model' of innovation and to make a case that earlier inventions grew out of social networks with characteristics similar to that of the World Wide Web and other modern communication networks. In this chapter we examine the evolution and network of contributions to the steam engine. In Chap. 2 we study the kinematics theory of machine design from the fifteenth to the nineteenth centuries beginning with one of the prime heroes of the genius theory, Leonardo da Vinci. As a particular example of complex machines we construct a network chart for the evolution of precision marine clocks. In Chap. 3 we describe the network of contributors to the creation of

the internal combustion engine and its effects on the automotive industry focusing on Henry Ford.

This discussion of engines naturally leads to early aviation in Chap. 4, where we describe a complex web of over 80 individuals and institutions covering the period of 1810–1910 from the time of George Cayley to the Wright brothers and Glenn Curtiss. This case study will provide examples of the importance of 'weak links' and the role of what Gladwell (2000) calls 'Connectors' such as Octave Chanute. We also describe in this chapter the use of an influence matrix and statistics of a link-node distribution curve.

The early development of wireless and radio communication is our fifth case study in Chap. 5. The seeds of wireless telegraphy grew out of the network surrounding the magnetic telegraph. Here again in addition to Marconi, Deforest and Armstrong, there is a complex set of up to fifty players spanning the work from Maxwell [c.1865] to the early days of radio and RCA's David Sarnoff in the 1920s.

It is interesting that inventors who show up in one technology network were also active in one or two other technologies. For example Lenoir, one of the pioneers of the internal combustion engine, received an award from France for his invention of an automated telegraph in 1865. Daimler, whose name is closely identified with automobiles and internal combustion engines, designed a lightweight engine for Count Zeppelin's dirigibles. The Rumkorff induction coil used in early internal combustion ignition systems was also employed in early wireless telegraphy systems. In the mid to late nineteenth century, one invention led to another, one scientific discovery was applied to several new inventions. Thus it should not be a surprise that social networks for different innovations often were interlocking through either common person or institution nodes or common critical technologies.

The mathematical and scientific ideas under the name of *Chaos Theory* are a branch of the mathematics of *nonlinear dynamical systems* In Chap. 6 we show how the seeds of twentieth century Chaos Theory in mathematical physics began to grow in the networks associated with the internal combustion engine and radio electronics. In our sixth detailed study of innovation we trace the mathematical discoveries of Henri Poincare in France at the beginning of the twentieth century to the weather models of Edward Lorenz at MIT and electrical circuits of Yoshisuke Ueda in Kyoto a half-century later. Chaos Theory has since morphed into *ComplexityTheory* in the late 1990s that in turn led to social network theories in the last decade. This example was chosen because of the author's close familiarity with chaotic and nonlinear dynamics, (Moon 1992), and because some fragments of the history of this science have begun to emerge in recent years.

In the Summary, Chap. 7, evidence for other historical innovation networks in science and technology, such as involved George Carrier in the development of air conditioning, will be presented though not in as detailed format.

In this final chapter we gather our data on the exponential rise of technical networks across two centuries, and present evidence for the rapid decrease in doubling time doubling time for growth of new technologies in the twenty-first century. Innovation networks that took half a century to grow in the late eighteenth century now have a doubling time of a year or less. We hope to bolster the thesis that for at least

the last 200 years, human society has progressed through the tension of both global cooperation and competition in the evolution of new technologies though social networks of people and institutions.

1.2 James Watt and the Steam Engine: Genius or Social Network?

As an introduction to the ideas in this book we examine the classic case of the evolution of steam power and describe the use of evolution diagrams, network diagrams and influence matrices. Our period of interest spans 1700–1800 before the exponential rise in the use of steam engines for manufacturing and transportation in the nineteenth century. This case is of interest because it predates the birth of the first communications revolution of the magnetic telegraph and the construction of rail networks. Our reference for the nodes and links in the steam engine network are classic histories by Thurston (1878), Lardner (1836) and Farey (1827). From Thurston we learn that preliminary engine trial and error was conducted in the seventeenth century. Here Huygens had proposed a gunpowder engine. Thomas Savery in England began to tackle the pumping of water out of deep mines in Cornwall. Papin an assistant to Huygens in Paris, went to England where he met Robert Boyle and introduced the moving piston into the steam engine. Thomas Newcomen corresponded with Robert Hooke and likely knew of Savery's engine before taking out a patent with John Calley on the first commercial steam engine for deep mines. Thus before the first steam engines were employed in the early eighteenth century, there was already established a network of scientists and inventors.

Principal Nodes in the Steam Engine Network 1700–1800:
Thomas Savery [1650–1715] built a working engine without a piston.
Denis Papin [1647–1712] Introduced a piston into the steam engine.
Thomas Newcomen [1664–1729] Built first partial vacuum, piston steam engine, 1712 for deep mine water pumping.
Joseph Black [1628–1799] Professor at Glascow University; studied latent heat of steam that led to James Watt's condensor.
James Watt [1736–1819] Instrument maker at Glascow University; added a condensor and other improvements to the Newcomen engine that significantly raised efficiency. Basic patents, circa 1769–1785.
Matthew Boulton [1728–1809] Business partner of James Watt. Used his factory system to produce Watt type engines.
John Smeaton [1724–1792] Early builder of Newcomen engines.
Jonathon Hornblower [1753–1815] In 1781 he invented a two piston, compound engine with low and high pressure cylinders, later built by Woolf.
Richard Trevithick [1771–1833] Built one of the first high-pressure steam engines and applied it to a moving vehicle.

Oliver Evans [1755–1819] American inventor who built a high-pressure steam engine, circa 1800.

1.3 Innovation Evolution Models and Network Diagrams

Historians of technology have long described models based on the evolution of innovation and inventions. (e.g. Basalla 1988) The economist and historian Joel Mokyr of Northwestern University has written a book, *The Lever of Riches* (Mokyr 1990), describing technological evolution from antiquity to the nineteenth century. He uses evolutionary concepts of selection and mutation to examine its impact on economic dynamics.

Sometimes innovation evolution is presented in a flow chart such as the one in Fig. 1.2 representing the succession of technologies leading to steam power. In this model, the nature of the connection between each technology is left vague.

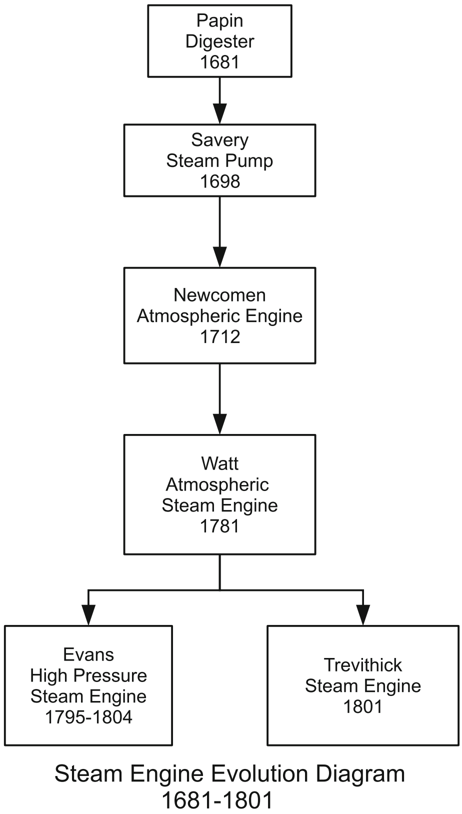

Fig. 1.2 Technology evolution flow diagram for the steam engine. Links do not denote any specific connection between inventions

To construct a social network diagram of steam engines we consult the work of Robert Thurston, [1839–1903], an American academic engineer with considerable practical experience with steam power. Thurston first taught at Stevens Institute of Technology in Hoboken, New Jersey in 1871. In 1873 he was appointed ambassador to the International Exhibition in Vienna. In 1885 the President of Cornell University persuaded Thurston to come to Ithaca and reorganize the College of Mechanical Engineering. Thurston's interest in machine design was on materials and thermodynamics, especially as they impacted the steam engine. Thurston was a firm believer in the evolution of technology. In his well-known treatise, *A History of the Growth of the Steam Engine,* Thurston (1878) wrote:

"*I propose to call attention to the fact that the history [of the steam engine] illustrates the very important truth: it Great inventions are never, and great discoveries are seldom, the work of any one mind. Every great invention is really either the aggregation of minor inventions or the final step of a progression. It is not a creation, but a growth—as truly as is that of the trees of the forest*."

In his *'History'* Thurston recited a litany of earlier contributors and inventors who made the steam engine possible. He began with the ancient Greeks—Hero's *aeolipile*, a rotating sphere with two arms expelling steam. He recognized the contributors in the Renaissance; Leonardo for his 'steam cannon' or *architonnerre*, and a Spaniard named Blasco de Garay [c. 1543], the Italian Giovanni Battista della Porta [c. 1601], and the French machine book author Solomon de Caus [1615]. From England Thurston named Edward Somerset, Marquis of Worcester, [c. 1663], and from the Netherlands Christian Huygens [c. 1680] who proposed a gunpowder engine as well as the Englishman Sir Robert Moray, Master Mechanic to the King, who measured the pressure-volume properties of steam.

Thurston's litany of working steam engines began with Thomas Savery, [c. 1698], Denys Papin [c. 1687], and finally the blacksmith from Dartmouth England, Thomas Newcomen [c.1705] whose machine concept had a life of over 75 years before the major contributions of James Watt (Fig. 1.3).

These new practical machines were considerably more complex in the variety of machine elements and kinematic mechanisms than the simple cylinder and piston of Leonardo da Vinci or the spherical vessel and cock valve of Solomon de Caus. The steam engines of Newcomen, Boulton and Watt and later engineers employed slider-crank and eccentric mechanisms, planet-sun epicycloid gear trains, straight-line linkages, flywheel and rotating ball speed regulators as well as complex valve control linkages (Fig. 1.4). This complexity increased further when the steam engine was employed in locomotives for railroad transportation. The evolution and network links for kinematic mechanisms in machines are discussed in Chap. 2.

The many variations of the steam engine in the nineteenth century spawned technical reviews and historical books. Two early histories were those by Farey (1827) and Lardner (1836). Thurston's *History of the Growth of the Steam Engine (Thurston 1878)* has become a classic and we use this source to construct a historical social network diagram for the steam engine as shown in Fig. 1.5

Fig. 1.3 Portrait of James Watt from the national portrait gallery London. Watt is studying his famous straight-line mechanism for converting the rotary motion of the rocker arm into straight-line motion of the piston. [Copy of this painting at Cornell University, School of Mechanical and Aerospace Engineering.] See also Fig. 1.4

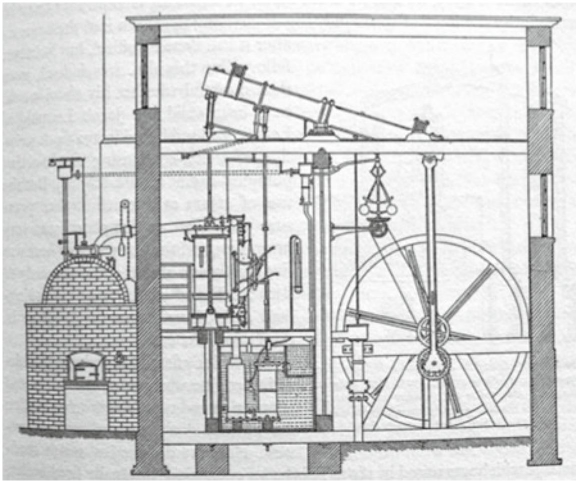

Fig. 1.4 Sketch of steam engine components of James Watt, 1784

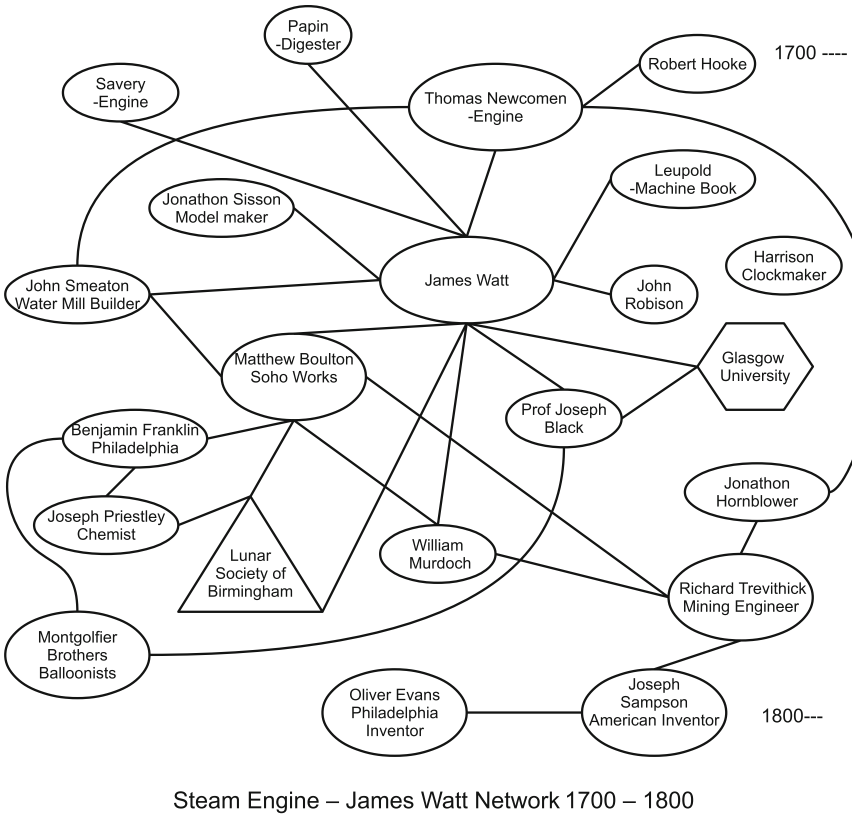

Fig. 1.5 Social network diagram for James Watt and the evolution of the steam engine. Human nodes are ellipses and institutional nodes are polygonal figures. Links denote specific interactions between nodes. [Based on Thurston (1878).]

1.3.1 Description of Selected Links in the Steam Engine Network

The many books on James Watt's contributions to the steam engine (see e.g., Rosen 2010), often tell of Watt's moment of epiphany on Glasgow Green when he conceived of the idea of a condenser for Newcomen's engine. But a closer look will reveal a human network surrounding the inventions of James Watt and his partner Matthew Boulton, connections between inventors, scientists and institutions (Tann 1981) (Fig. 1.5). Links between nodes include personal contacts such as developed in the Lunar Society of Birmingham as well as letters, books and historical links. This network does not diminish the contributions of Watt to steam power, but makes more explicit his connections to a community of other contributors to the technology and to the science of steam power and thermodynamics.

This network in Fig. 1.5 shows the connection between artisan inventors such as James Watt and scientist Professor Joseph Black of Glasgow University. It also shows the connections between Newcomen's earlier steam engine and engineers Smeaton and Trevithick who tried to improve the Newcomen engines without violating the Boulton-Watt patents. Although this incomplete network only contains 22 nodes, it also shows the connection between Great Britain and North America through the links of Benjamin Franklin and Oliver Evans [1755–1819]. Evans received America's third patent and invented a high-pressure steam engine that eventually replaced the Watt atmospheric steam engine. The Lunar Society node is based on a book describing the network of men in and near Birmingham who met regularly and exchanged scientific and technical ideas (see Uglow 2002).

After reading Thurston's history of steam power and thermodynamics and reflecting on the network of Fig. 1.5, can we really say who invented the steam engine? As we shall see in the other examples in this book ascribing credit for new inventions and innovations to one or two individuals is almost impossible in the light of the evidence of a more detailed history of invention. Yet it is difficult for our society to let go of the appellation "inventor".

1.3.2 James Watt's 'Epiphany' Story

One important characteristic of the genius inventor myths is the moment-of-truth or epiphany story, often told many years later by the inventor and subsequently embellished by personal friends, family or corporate interests. Robert Thurston's history of the steam engine quotes Watt's narrative of his ah-ha moment;

"*I had gone for a walk on a fine Sabbath afternoon—{on Glasgow commons}—I was thinking about the engine at the time and had gone as far as the herd's house when the idea come into my mind that, as steam is an elastic body, it would rush into a vacuum and if communication there made between cylinder and an exhausted vessel, it would rush into it and might be there condensed without cooling the cylinder."—" I had not walked further that the Golf house when the whole thing was arranged in my mind*."

It is not difficult to see how such a story would appeal to a biographer as well as his or her readers: the instant revelation, the magic moment of creativity. Another interpretation of these innovation stories is the 'avalanche' model where the historical network of the information commons becomes sufficiently complete that someone in the network is able to piece the puzzle together and create a new idea or product.

1.3.3 Links to the Aeronautics Network

The network in Fig. 1.5 also shows links between inventors and engineers of steam power and of the nascent field of aerial flight and ballooning. Franklin was a witness to the flights of the Montgolfier brothers in 1783 in Paris, and sent a letter to Joseph Banks at the Royal Society that led Boulton and Priestley to generate hydrogen gas

and demonstrate ballooning principles in England. As we shall see in Chap. 4 on early aviation, George Cayley began to ponder the difficulties of using steam engines in aerial machines and speculated on the use of internal combustion engines for flight vehicles.

1.4 History of Innovation Studies

There are many definitions of innovation. In this book, we use the term '*innovation'* to denote new scientific and technical *ideas* and the term '*invention*' to denote new *artifacts* and *products* such as the steam engine, radio or cell phones, for example.

Scholars have posited the idea of a societal role in innovation and evolution. The idea of *prosopography* in sociology was developed in the 1930s as the study of the interaction of a number of players in history. It also has roots in the nineteenth century through Francis Galton [1822–1911] who used many biographies of British scientists to study heredity, environment and genius. The concept of collective biographies was used by the German historian Theodor Mummisen to the study of the Roman Empire. He defined;

> Prosopography [as] a modern word for the study of individual persons in a larger context—[it] aims to establish the social context of groups such as their ethnic and regional origins, family connections and careers (see Keats-Rohan 2007).

Earlier studies such as Everett Rogers (1962) classic book examined the diffusion of innovations such as agricultural science and medical practice in rural America. Rogers used the term 'social systems' instead of 'social networks' and included in his system individuals and organizations. He also referred to communication channels and used the 'S' curve, discussed below, to model the acceleration and decline of innovation into a marketplace. Later studies have examined the penetration of new technologies into society. For example, Hughes (1983) has studied the spread of electrification in Western societies in his book *Networks of Power.*

Although there are precedents in prosopography and network theory connecting different persons in the evolution of technical and scientific ideas, the *Historical Innovation Networks* discussed in this book extends the ideas of prosopography by using elementary, mathematical constructs of network theory.

The use of evolution and network diagrams has been used in the history of art. In 1936, Alfred Barr, the first director of the Museum of Modern Art (MOMA) in New York, drew a famous evolution diagram connecting cubism and abstract art. In a recent exhibition at MOMA, "*Inventing Abstraction*" Paul Ingram of Columbia University presented a network diagram connecting many of the artists in the period 1900–1930 who were creating abstract art (Dickerman 2013).

The Lithuanian-American artist George Maciunas, a member of the New York avant-garde art scene in the 1960s, developed a 6-foot by 12-foot long graphical history of art. A recent book, *Maciunas' Learning Machines,* by Schmidt-Burkhardt (2011) describes the extensive use of complex network diagrams by Maciunas

connecting many of the players in the Dada and avant-garde art movements of the early twentieth century.

In the modern era, mathematicians have constructed family trees tracing the students of famous and not so famous professors of mathematics. [See the Mathematics Genealogy Project of the American Mathematics Society] Using the Internet, we can also trace the network of citations of scientific papers connecting scientists in one field with others in disparate fields who cite the same paper.

Science Network Studies

In an earlier work, de Solla Price (1965a, b) studied the network of scientists by statistically analyzing the citations they made of other research papers. He showed that the number of papers N that received k citations N(k) followed a decreasing power law, that is a few papers were cited frequently while most were hardly cited at all. He also showed that as a scientific field evolves, at least half the citations are to papers recently published. This implies that the leaders of a field mainly cited the their current peers and that there was a tight group of scientists in any developing field who were in constant awareness of each other's work. Science progresses in a wave with a tight knit group of researchers at the forefront.

Since the work of de Solla Price, there has been a continuing study of the sociology of science sometimes called '*scientometrics*'. Many of these studies rely on the research citation data readily available on the Web. Citations may be considered 'formal' links in a social network model but they do not account for the informal links such as letters and email exchanges, or oral exchanges, international meetings and workshops and personal contacts. The studies presented in this book rely on data in many narrative histories of a specific technical field. Hence the size of the data sets of nodes and links is less than hundreds and much less than the thousands of citations in the study of contemporary science. Nonetheless, the emerging patterns of exponential growth of nodes and links and the concomitant growth in machine performance and market penetration suggest that technological networks behave in ways similar to that of science but with more subtle kinds of links.

Finally in the fields of electrical engineering and computer science there is a mathematical theory of networks that uses graph theory and matrix mathematics to represent the connections between elements or nodes in the network (see e.g., Newman 2003). In our book, we sample each of these traditions of innovation and network theory and attempt to apply some of these ideas to examples from the history of technical and scientific innovation, especially from the late eighteenth to the early twentieth centuries.

1.5 Historical Innovation Networks

A *historical innovation network* consists of a set of persons [inventors, engineers, scientists, artisans], organizations [e.g. universities, Royal Societies] and social events such as international expositions, each of which is called a *node*. This collection of nodes has inter-nodal connections called *links* (or edges). A general historical innovation network is shown in Fig. 1.6. Links between person-nodes are created

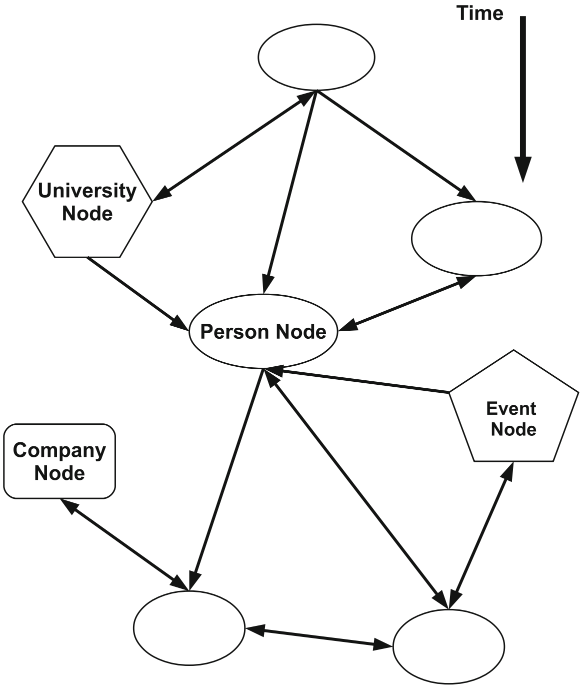

Fig. 1.6 General components of a historical innovation network diagram

by friendship, letter exchange, writings, books, and financial interest, to mention a few. Links between person-nodes and organizations involve membership, professorial appointments, education of students etc. Connections between event nodes and person-nodes are created by attendance or by proceedings etc.

Each link is either directional or bidirectional. Links between nodes in different generations are unidirectional. For example in early aviation Lilienthal could influence the Wright brothers but they did not influence Lilienthal because he died in 1896 three years before the brothers became interested in flight [1899]. In social network theory, nodes can have attributes called *fitness*, which measures the importance of the node or link. For example in aviation, the Wright brothers and Lilienthal would be high fitness nodes. In the internal combustion network, Nikolas Otto would be a high fitness node. Unlike social networks such as the World Wide Web, or *Facebook*, a history network spans generations linking person nodes living in one generation with dead person nodes in an earlier generation. In a history network, nodes can be connected across generations. Historical Innovation/Invention Networks [HIN] also evolve as new nodes are added and new links are created between new players. In HIN, there can be *sub-networks* that can focus on a specific component; e.g. in aviation one can focus on lightweight engine evolution, or the wing design as well as the underlying aerodynamic theory development. In radio one can focus on wireless telegraphy or on vacuum tube development.

The difference between a pure narrative history and a history network theory, is that in the latter, the historian is obliged to determine if there are links between all of the nodes in the network. Thus if a new node (player) is mentioned, its links to all the other nodes must be established. The analysis in this book uses an influence matrix, a network graph and an event-node timeline graph.

1.5.1 Influence Matrices

An *influence matrix* is an array of numbers M[NS, NT] where NS are the source nodes of the influence (rows) and NT are the terminus nodes of the directed influence links (columns). For example in the eighteenth century steam engine network, Newcomen is an NS link for James Watt, whereas Watt is a source node for the Trevithick, the inventor of a steam railroad engine. The matrix for the steam engine network in Fig. 1.7 is 21×21 nodes and the entries are not weighted and contain only zeroes and ones. In this book, node-pairs that were contemporary were assigned both outgoing and incoming links; it was assumed that each influenced the other. Earlier generation nodes connecting later nodes were assumed to have only outgoing links. A more detailed HIN would include weighted, as well as directed links. We could also scale the importance of the nodes with respect to the advance of the technology, however we did not attempt to assign a such node scale for the case studies in this book.

A related representation is the *Adjacency Matrix* for the steam engine network shown in Fig. 1.7. Without assigning direction of influence, this matrix is symmetric and only the lower half is shown. The nodes were listed arbitrarily by numbers of links attached to the node. Not surprisingly, James Watt and Michael Boulton had the

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1 Watt	0																				
2 Boulton	**1**	0																			
3 Newcomen	**1**	0	0																		
4 Trevithick	0	**1**	0	0																	
5 Smeaton	**1**	**1**	**1**	0	0																
6 Black	**1**	0	0	0	0	0															
7 Murdock	**1**	**1**	0	**1**	0	0	0														
8 Lunar	**1**	**1**	0	0	0	0	0	0													
9 Franklin	0	**1**	0	0	0	0	0	0	0												
10 Priestly	0	0	0	0	0	0	**1**	**1**	0	0											
11 Glasgow	0	0	0	0	0	**1**	0	0	0	0	0										
12 Hornblow.	**1**	0	**1**	**1**	0	0	0	0	0	0	0	0									
13 Montgolfi.	0	0	0	0	0	**1**	0	**1**	0	0	0	0	0								
14 Sampson	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0							
15 Evans	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0						
16 Robison	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
17 Leupold	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
18 Sisson	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
19 Savery	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
20 Papin	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
21 Hooke	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 1.7 Adjacency matrix for the influence matrix of James Watt and the steam engine social network based on Fig. 1.5 and Thurston (1878)

highest number of links. This suggests a modified definition of the genius theory of invention where the nodes with the greatest influence or number of links are anointed one of the principal innovators. This approach recognizes the importance of creative people as well as acknowledges the role of other players in the innovation network.

1.6 Introduction to the Theory of Graphs

The above example is one of many similar problems that fall under the mathematical study of *graph theory* (see e.g. Wilson and Watkins 1990). Such problems date back to the time of Euler in the eighteenth C. Graphs arise in such diverse areas as computer science, electrical circuits, transportation networks, economics and in biochemistry of macromolecules. The National Institute of Health in the US has a "Human Connectome Project" run by UCLA. Using brain scans scientists can trace the neural pathways through the brain.

Recently scientists have used graph theory to address the complexities of the World-Wide Web and other social networks involving millions of nodes. [See e.g. Easley and Kleinberg (2010) for a college level introduction to applications of network theory. For a more advanced treatment see Newman et al. (2003).] While our goal is to focus on the history and not the mathematics of innovation networks, there are some basic ideas and properties of graphs that will be useful for our discussion.

Below is an example of an abstract graph (Fig. 1.8) that can be represented either as a pictorial object with nodes and links or as a matrix (Fig. 1.9). The rows and columns of the matrix are labeled with the names of the nodes (circles). The influence matrix (Fig. 1.9 Top) is constructed as follows: If there is a directed link from e.g. node D to node C, we place a '1' in the D row in the 'C' column. If there is a bidirectional link between A and B, we place a '1' in the A row in the B column and place a '1' in the B row in the A column. The diagonal of the matrix has zeroes and if there are no links between nodes the corresponding entries are zeroes. To construct the Adjacency Matrix in Fig. 1.9 bottom, we assume that all the links are bidirectional and the matrix becomes symmetric.

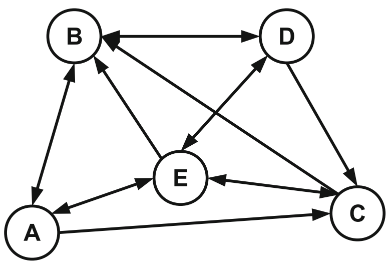

Fig. 1.8 Five-node network with one-way and two-way links

Fig. 1.9 **a** *Top*: Influence matrix for the example in Fig. 1.8. **b** *Bottom*: Adjacency matrix for network example in Fig. 1.8a. Note the symmetry

(a)

Nodes	A	B	C	D	E
A	0	1	1	0	1
B	1	0	0	1	0
C	0	1	0	0	1
D	0	1	1	0	1
E	1	1	1	1	0

(b)

Nodes	A	B	C	D	E
A	0	1	1	0	1
B	1	0	1	1	1
C	1	1	0	1	1
D	0	1	1	0	1
E	1	1	1	1	0

The influence and adjacency matrices for the graph in Fig. 1.8 are shown in Fig. 1.9.

One of the measures we seek to discover in HIN is the average distance between different nodes. For example in the graph of Fig. 1.8, the 'distance' between node A and D is two links. In modern social networks, we call this the *degrees of separation* (see e.g. Watts 2003). For the steam engine network represented by the matrix in Fig. 1.7 we find a distribution of separation paths in this network shown in Fig. 1.10. For example the 'distance' between Watt and Benjamin Franklin in Fig. 1.5 is two links while the distance between Watt and Oliver Evans is four links. Most of the nodes in Watt's network are only separated by 1,2 or 3 links. Algorithms in graph theory that address this problem are called 'shortest path' algorithms and use the adjacency matrix similar to that in Fig. 1.7 (see e.g. Wilson and Watkins 1990 , Sect. 8.2).

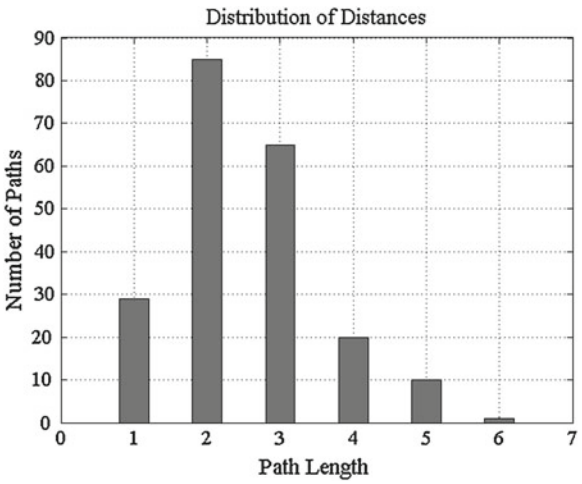

Fig. 1.10 Distribution of number of links in the path between any two nodes for the steam engine network surrounding James Watt in Fig. 1.5 and matrix in Fig. 1.7

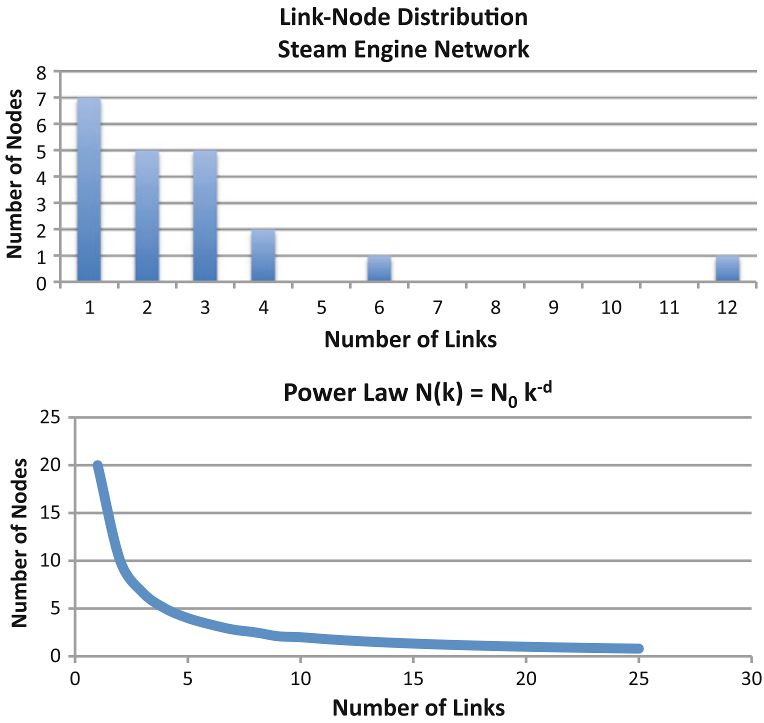

Fig. 1.11 *Top*: Distribution of the number of links per node for the steam engine network of Fig. 1.5. *Bottom*: Power law function for d = 1

The data in Fig. 1.7 was generated with a computer algorithm *'graphshortestpath'* in the Bioinformatics Toolbox of the software package MATLAB.

A classic property of networks is the distribution of number of links. In the steam engine network Fig. 1.5, there are a few nodes with a relatively high number of links and many nodes with few or only one link, as illustrated in Fig. 1.11. If we increase the number of nodes in this network, we might expect to fit a continuous curve drawn through the points in the graph. Such a distribution is called a *scale-free network* since there is no characteristic number of links between nodes (see e.g. Barabasi 2003). Modern networks such as the World Wide Web also have a scale free property of links and nodes.

Thus combining historical studies of a technology, such as Thurston's history of steam power, along with modern mathematical tools from graph theory and computer algorithms [e.g. the influence and adjacency matrices], the modern historian of science and technology can obtain quantitative measures of the creation of new technical and scientific ideas. This does not displace the traditional narrative history methodology, but enhances and extends the understanding of the societal role in the creative process in science and technology.

Compared to the historical networks in this book, with only a few dozen nodes and perhaps a few hundred links, the study of modern social networks such as the World-Wide Web has millions of nodes and links. Modern network analysis affords an entire suite of statistical measures to characterize these large networks as described in a review paper by M.E.I. Newman (2003). These mathematical tools measure network properties such as clustering, path length distributions between nodes as in Fig. 1.10, mixing patterns, so-called 'small world' effects, degree correlations and more. We shall not pursue these advanced properties of networks here. First this is an introductory monograph on history of invention, and second the small number of nodes and links in our networks do not make for statistical rigor. Nonetheless, we will seek to use some of the simplest tools of general network theory as illustrated above. Readers seeking deeper knowledge of networks should consult the works of Newman, Barabasi, Watts and their colleagues. (See Newman et al. 2003 for a collection of research papers surveying modern network theory, or the introductory college textbook of Easley and Kleinberg 2010).

1.6.1 Growth of a Network Knowledge Commons: Timelines and Social Networks

One of the classic tools of historians is the *event timeline graph*. Important events in an historical subject are marked on a horizontal or vertical time axis similar to the chart in Fig. 1.12. In proposing a network model for innovation, we assume that technical and scientific information accumulates in a subject area, such as steam engine technology, and subsequently influences nodes and events in the future. Therefore we show a sample timeline chart with a simultaneous growth of an associated social network. Since accumulated knowledge has value for the network, in Fig. 1.13 we show the integrated number of events with time for an exponential growth.

We propose in this book that the exponential growth for different innovation fields, are correlated with the growth in the network. Accumulated knowledge feeds the growth of the network and vise versa. Thus one of the tools for studying growing networks, is the integrated measures of innovation information. In modern scientific fields, we can measure the growth in published research papers. For earlier times we must seek other measures such as the number of patents filed or number of machines built over a given time period.

One measure of the accumulated network knowledge is to look at the density of events in the history of a scientific or technical field. In the case of the steam engine, new materials were used, new topologies and mechanical components were developed and new thermodynamic concepts were employed as the steam engine evolved. Also new engines were built and tested in the field and this experience gave confidence to future contributors to the field. Each new machine also created a competitive incentive for future designers and entrepreneurs to build a bigger and better machine. This accumulation of knowledge and experience contributed to the

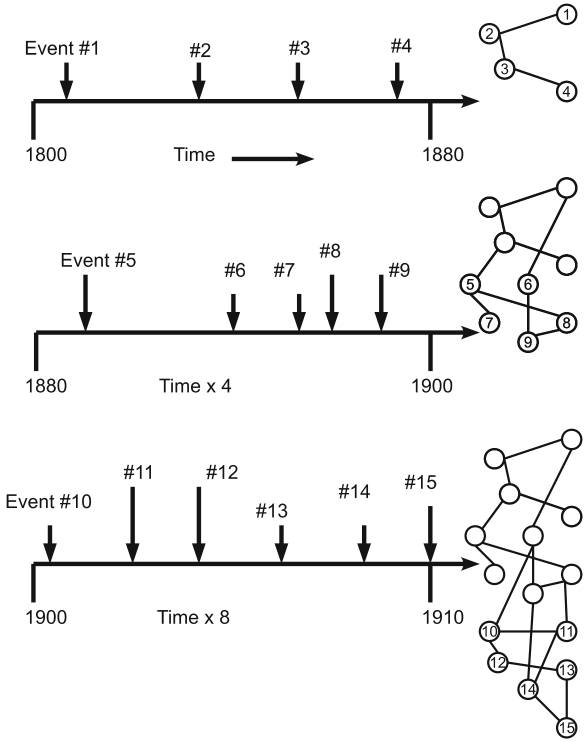

Fig. 1.12 Sample event timeline and growth of associated innovation network. The growth of the number of events and/or nodes versus time is plotted in Fig. 1.13a, b

dynamics of the growth of the network. One could plot the frequency with which new technical events were happening. However to smooth out the noise and randomness in the event history, we propose to integrate or add the number of events in a function called *G(k)* from time t_0 to time t_k. In mathematical notation we would write;

$$G(k) = \sum ß_i e_i; \{i = 0, 1, 2, 3 \ldots k\}$$

Here $\sum$ denotes a summation operation, the event numbers $\{e_i\}$ are all equal to '1', and the event weights $\{ß_i\}$ range from zero to one, i.e. $0 < ß_I < 1$. If an event is very important then $ß_I = 1$, if an event has marginal impact on the field, then $ß_I = 0.1$. If a new technology is advancing very rapidly, then when G is plotted in time it will exhibit a sharp rise, which we propose is also indicative of a rapid growth in the innovation network. A hypothetic example is shown below in Figs. 1.12 and 1.13. In Fig. 1.13b, the vertical scale is stretched into a logarithmic scale and the curved exponential curve in Fig. 1.13a looks closer to a straight line. This is a technique used by experimenters to quickly see if data appears to be an exponential function of time, rising very rapidly in time.

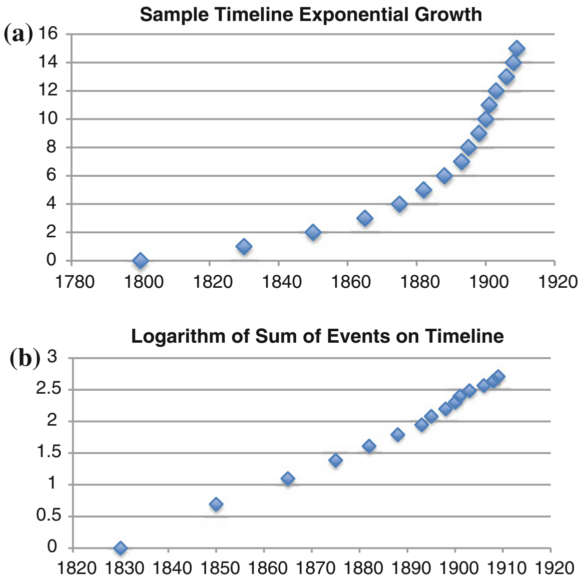

Fig. 1.13 **a** Graph of number of nodes or timeline events for a sample innovation field versus time for exponential growth. **b** Plot of Logarithm of the number of events versus time. The bi-linear structure of this data suggests exponential growth with lower rate in the early years and faster exponential growth of the field in later years

Historical data for the growth of steam engine technology is shown in the figures below using timeline data from Thurston (1878). Figure 1.14 illustrates the partial event timeline for the steam engine and the accumulated number of events as a measure of the steam engine knowledge commons is plotted in Fig. 1.15. Another measure of innovation growth in the use of steam power is the number of units in use in the UK, shown in Fig. 1.16.

Can one construct a model for the growth of innovation networks? Is it possible to predict when a field or product will undergo exponential growth based on early observation of the network dynamics? Using a timeline of events in the history of the steam engine from Thurston (1878) we see the increase in the number of events in the development of the steam engine in Fig. 1.15. We assert that this is proportional to the increase in the nodes in the network diagram of Fig. 1.5 similar to that in Fig. 1.12. In the growth of the integrated events curve of Fig. 1.15a, we can see an initial linear growth in the early part of the eighteenth century and then a more rapid rise in the later half of the eighteenth century. A similar sharp rise in the number of steam engines produced in the UK is shown in Fig. 1.16. It is postulated that the increase of innovation node growth and steam engine product growth are coupled. That is *behind every new emergence of a technical product is a growing social network associated with that technology.*

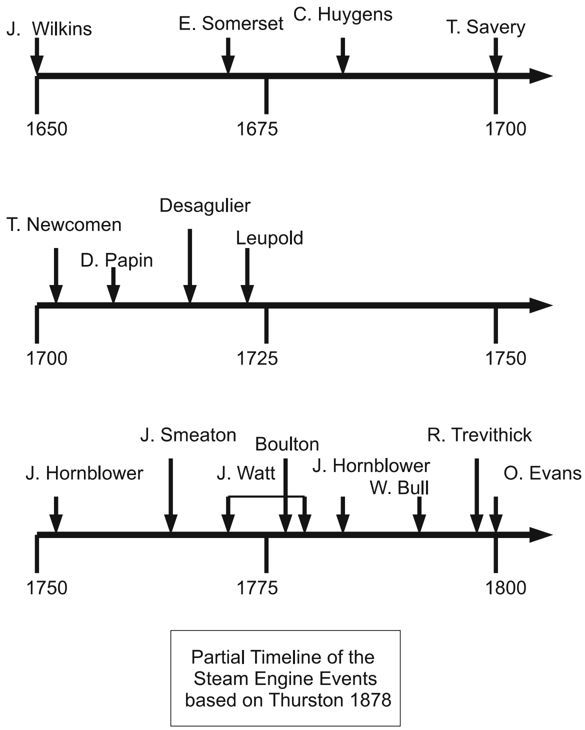

Fig. 1.14 Partial timeline for significant events in the development of the steam engine based on Thurston's history book of 1878

As we shall see in other examples, this behavior seems to be a typical pattern in the evolution of technical and scientific ideas. Initially there is a steady or linear growth of players or nodes that at some time begins to rise in a nonlinear or exponential manner. It is the recognition of the initial time of this exponential rise that makes millionaires out of investors of new technologies.

We must use caution in applying such analysis to new technologies in that the rise in the product penetration into the market, as shown in Fig. 1.16, usually lags the rise in the developmental events as illustrated in Fig. 1.15a for the steam engine. It is usually easier to measure production, but it is more difficult to discover the moment of exponential growth of the social network that is responsible for the new product or service.

In biology one is familiar with the maxim that without mortality factors, populations grow in proportion to the population. Translated into mathematical terms such growth is called *exponential* increase. The formulation of mathematical models of Malthusian population growth can be dated to Verhulst in 1846 (Usher 1929). Similar growth functions are found in chemical and nuclear physics. Such models embody the idea that with more elements or nodes in the system, more will interact and create more nodes.

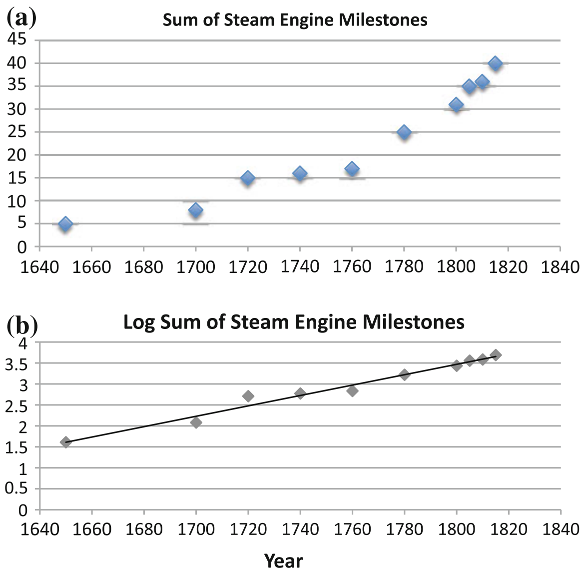

Fig. 1.15 **a** Growth of number of events in the steam engine network 1700–1800 of Fig. 1.14 based on Thurston (1878). **b** Logarithm of **a**: linear line suggests a single the exponential function will describe the growth rate

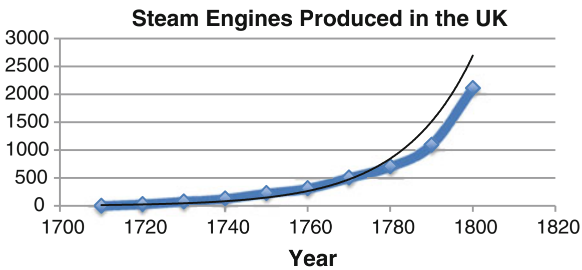

Fig. 1.16 Exponential growth in the number of steam engines produced in the UK from the time of Newcomen [1712] to the end of the Watt–Boulton patents, 1800. The data includes machines from over a dozen manufacturers (Kenefsky and Robey 1980). Solid line is the best fit exponential function using EXCEL

Of course populations cannot grow to infinite size due to limitations of food, energy and resources as well as predatory behavior of other species. In bio-mathematics there is the famous two-specie model of the 'predator and prey' in which as a primary specie grows, it provides more food for the predator species. As the predator consumes the primary species and depletes its own food supply, the predator population declines allowing the primary group to increase its numbers again. Both species exhibit oscillatory population histories but out of phase with each other.

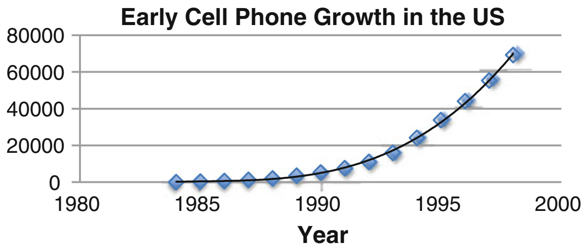

Fig. 1.17 US Cell Phone Subscribers from 1985–1998 (Data from *The World Almanac, 2000,* page 628) Exponential curve fit using EXCEL

The history of technology and invention has many cases of exponential growth and decline, similar to the population growth models in biology (see e.g. Rogers 1962). For example in the early days of the cell phone, 1985–1998, the number of customers who became a subscriber grew exponentially as shown in Fig. 1.17.

When social networks are attendant to the fast growth of a new technical idea or scientific theory, the rate of node increase is often proportional to the number of nodes, and the number of links grows in a similar manner.

Earlier generations of historians of technology such as Usher (1929) have asked similar questions; 'How do new things happen?" In his seminal *History of Mechanical Inventions,* the opening chapters addresses the so-called 'great-man' theory of invention *theory of invention*. Usher discusses humankind's propensity for "novelty in thought and action". Thus when human societies are free to embrace new ideas their natural desire to communicate will spread that idea in an exponential manner. The thesis in this book is that the early exponential growth of new technologies and innovations is linked to the growth of a social network attendant to that innovation.

1.7 Mathematical Models for Network Growth

Given the sharply rising curves associated with the advance of the steam engine in Figs. 1.15 and 1.16, it is tempting to postulate a mathematical model for the increase in nodes in a historical innovation network. In general we would imagine a sequence of node growth, $\mathbf{N}_n$, along with a set of links, $\mathbf{L}_n$, where 'n' is a measure of the passage of time, and the next node set $\mathbf{N}_{n+1}$, $\mathbf{L}_{n+1}$, are functions of the previous number of nodes and links. This general relationship might be written in the following equations:

Node Growth

$$\mathbf{N}_{n+1} = \mathbf{N}_n + \mathbf{G}\{\mathbf{N}_n, \mathbf{L}_n\};$$

Link Growth

$$\mathbf{L}_{n+1} = \mathbf{L}_n + \mathbf{F}\{\mathbf{N}_n, \mathbf{L}_n\}$$

The functions **G** and **F** above can be either deterministic or based on probability theory. In modern theories of social networks such as Facebook, where millions of transactions are occurring every day, probability models are used to predict growth. Attempts to predict the growth of historical innovation networks or modern technology networks might need another approach than probabilistic models since the number of nodes is often orders of magnitude lower than networks such as the World-Wide Web.

Models for the growth of networks in sociology date back to the 1950s and 1960s in especially the work of Derek de Solla Price (1965a, b), mentioned above. These models often assume that the increase in the number of nodes and links is proportional to the current number of nodes and links. Modern growth models have been proposed by Barabasi and Albert (1999). These and other models are reviewed by Newman (2003).

In this book however our focus is on the development of technical and scientific ideas that result from the evolution of a social network. Thus we are interested in the slow rise and rapid growth stages of a science and technology. To capture this phenomena we propose a network node growth that is proportional to a constant plus a term proportional to the number of nodes; i.e. if we define

$$\Delta \mathrm{N} = \mathrm{N}_{\mathrm{n}+1} - \mathrm{N}_{\mathrm{n}}$$
$$\Delta \mathrm{N} = [a + b\mathrm{N}]\Delta t$$

For early times in this process, this model predicts that N(t) growth is proportional to time i.e. N = at.

For later times, this model predicts that N(t) grows exponentially i.e.

$$\mathrm{N} \Rightarrow \mathrm{N}_0 e^{bt}$$

An example of such a node growth model for a = 2, b = 1/4 is shown in Fig. 1.18 where the time unit is decades. The pure linear model with a = 2 is one in which the number of nodes doubles each decade. The combined linear and exponential model shown as the top curve increases significantly faster than the linear growth curve

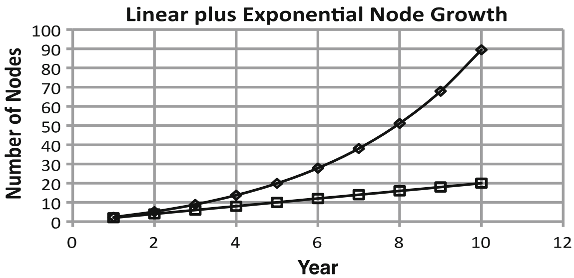

Fig. 1.18 Node growth model: *Bottom*: Linear growth; *Top*: Linear plus exponential growth $a = 2$; $b = 1/4$

below. The increase in the network nodes is proportional to the number of nodes as well as time.

Some technical developments such as ballooning in the nineteenth century [Chap. 4] exhibit mainly linear growth in time, while others such as radio development exhibit exponential phenomenon [Chap. 5]. Linear growth implies that the historical network does not play a strong role. New players come into the field because of their inherent interest and not because others are in the field. On the other hand, when new players are inspired by the aggregate of players or nodes in the network, the network grows more rapidly and appears exponential. Exponential growth is like a chain reaction where the larger the number of nodes the larger the growth rate in the network. We will find this phenomenon in many of the innovation examples in this book.

As we shall see in Chap. 4 on aviation, as historical networks advance, not only does the number of nodes grow, but so also does the number of links between the nodes. And in the age of the telegraph and the early telephone age, this growth in both the nodes and links occurs in an exponential way.

Not all examples of historical innovation undergo exponential growth. In the next chapter we show that in the period between the Renaissance and the Industrial revolution, there is evidence of growth in machine technology knowledge but it grew in a linear manner, most likely because the information and transportation networks that underpin modern technological development were not in place until the nineteenth century.

The study of the dynamics of technological change has been an active field for over a half century not only in history of technology and sociology but also in economics (see e.g. Mansfield 1968). It is beyond the scope of this book to survey all of these sources. Econometric models of technological dynamics often begin with statistical data. Our approach in this book is history based, beginning with the minutia of historical biographies and surveys of technology to find nodes and links and then applying statistical and mathematical methods where possible.

1.7.1 Growth Models and the "S" Curve

There have been many attempts to model the growth and evolution of observable phenomena such as populations, disease, pollution, and new product market penetration. In these phenomena, there are often four phases of change; early slow growth, rapid exponential growth, leveling off and decline. For example the use of telegrams began in the early to mid nineteenth century, accelerated in the late nineteenth, leveled off in the early twentieth century and declined and disappeared in the late twentieth century. One mathematical model that captures the first three phases is the "S" curve, shown in Figs. 1.19 and 1.20 (see e.g. Rogers 1962; Bejan and Lorente 2011). This model is often useful in capturing product or service penetration in a market for a new drug or a new fashion craze. A mathematical curve that has a similar shape is the sigmoid function plotted in Fig. 1.19.

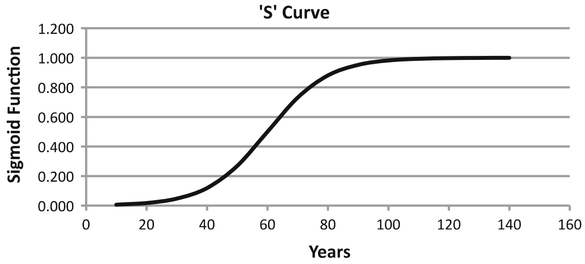

Fig. 1.19 Graph of 'S' Curve or sigmoid function $= [1/(1+exp\{-t+60\})]$; this function shows slow growth, then rapid acceleration and saturation

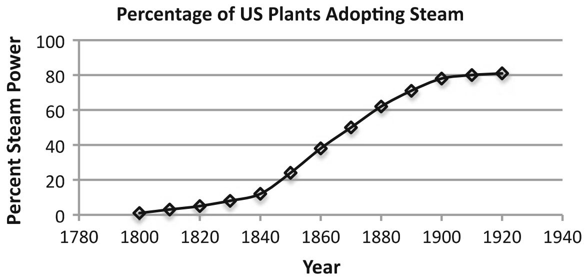

Fig. 1.20 An 'S' curve. Percentage of manufacturing plants in the US that replaced water power with steam power, 1800–1920. (From Atack et al. 1978.)

In technology, new product numbers first rise, then level off as the ultimate number of potential customers is finite and as new products ('predators') replace the customer need for the original technology (Rogers 1962). This phenomenon is sometimes called an "S" curve. An example of S-curve growth for the use of steam power in the United States is shown in Fig. 1.20. The authors noted that conversion to steam was greatest in the Midwest where waterpower was scarce and made least progress in New England where there was a long history of hydropower-based manufacturing. Hence the asymptote in Fig. 1.20 is 80% steam power.

The 'S' curve has mathematical roots in the modeling of population growth. Pierre-Francois Verhulst [1804–1849] used such a model, in 1838, to describe the constraints on human populations. In such a model the increase in the population or number of nodes in network theory ΔN is assumed to be proportional to both a linear and quadratic function of N;

$$\Delta N = aN(1 - N/N_0) \quad \Delta t.$$

The nonlinear term N^2, represents the constraints on the expansion of the population when it grows too large. When ΔN and Δt are small, the limit of this expression is a differential equation known as the *logistic equation*. Its solution where N is given as a function of time takes the form of the sigmoid function in Fig. 1.19.

$$N = N_0/(1 + e^{-at}).$$

The Nobel Prize winner Ilya Prigogine has written of self-organizational principles in natural and societal systems and uses the logistic equation to model the growth of insect colonies as well as the economic growth of cities (Nicolis and Prigogine 1989) Economists have also used the logistic equation to describe market penetration of a new innovation (see e.g. Silverberg et al. 1988).

Literature in the history of technology contains many examples of technological growth (see e.g. de Solla Price 1965a, b, 1951). In this book we present evidence that such increases arise from the emergence of social networks between inventors, artisans, scientists, educational institutions and industrial organizations.

As technologies mature, the role of the person-node diminishes and the importance of the manufacturing company node increases. An example of this is the growth of the internal combustion industry described in Chap. 3. Although personalities such as Otto and Daimler were important nodes in the early period say 1860–1890, by the turn of the century there were many licensed companies producing engines. This transition was enabled by a machine tool infrastructure already in place as a result of the earlier steam engine technology and its role in building railroads, steamships and manufacturing technology. A similar scenario existed in the evolution of wireless and radio technology, described in Chap. 5, where the existence of both telegraph and electric generation technologies allowed mature companies to move into the new radio age with relative ease.

The transition of HIN based on individual nodes to networks based on institutional nodes such as research universities and corporations would be an interesting study but is beyond this book except anecdotal examples.

1.8 Lessons from History Innovation Networks

Anticipating the results of succeeding chapters, the case studies of innovation social networks described in this book suggest some lessons for modern innovation.

(i) New ideas in science and technology are often the product of both evolution and complex social networks.
(ii) New technical artifacts are usually preceded by the emergence of other technologies, e.g. the internal combustion engine preceded aviation.
(iii) Secrecy and patents do not seem to inhibit the exponential growth of new ideas.
(iv) Both physical communication and transportation infrastructure networks are necessary to the growth of innovation social networks.
(v) Although artisans played a major role in late eighteenth and early nineteenth C. technologies, educational and research institutions have become important nodes in modern innovation networks.
(vi) Behind every emergence of a new technical product is a growing social network associated with that technology.

The succeeding chapters expand on these themes through detailed discussion of specific examples of innovation and invention.

In contrast to the romantic view of scientific creativity, modern engineering education stresses the collaborative nature of technical design. The engineering team approach as a tool for creating new robotic machines is now entrenched in many high schools and engineering colleges. Student team competitions in robotics, mathematics, efficient home design and racecars are all the rage in engineering education today. The irony of course is that many of the young people attracted to these teams are also inspired by the genius stories of invention. Many see themselves as becoming the hero or heroine inventors of the future.

One bastion of the isolated scientist model is the PhD research dissertation system. But in many areas of science, such as gene theory and high-energy physics, there are teams of up to hundreds of biologists and physicists involved. Recent examples are the Large Hadron Collider Project at CERN in Switzerland or the Mars planetary missions of NASA. [CERN boasts that 10,000 scientists or half the world's particle physicists come to CERN to do research.] Many admit that modern science has become a global collaborative effort but still harbor the dream of the Nobel Prize; the ultimate embodiment of the 'genius' model of scientific innovation. Berkun (2010) in *The Myth of Innovation* makes a case for societal and organizational roles in the creation of new technical ideas and products.

1.8.1 Self-Organized Critical State Models for Innovation

In Fig. 1.11 we presented steam engine statistics for the number of nodes N(k) with k links as a power law function $N = N_0 k^{-d}$. This distribution is similar for the World-Wide Web. Statistics for earthquakes, forest fires, the growth of cities, all have power law properties similar to modern networks such as the World-Wide Web. For earthquakes, N is the number of quakes over time with strength 'k'. For demographics, N is the population and 'k' is the rank from high to low. In the last two decades physicists have attempted to link these phenomena to similar behavior in the physical world of science such as the properties of sand piles, avalanches and magnetic domains in materials. (Buchanan 2000) Physicists have tried to apply a mathematical theory called *self-organized criticality* or SOC, to such phenomena (Bak 1996). The appellation '*criticality*' refers to the possibility that the system will experience a significant event such as an earthquake or an avalanche in a sand pile. '*Self-organized'* implies that after such an event, the system resets itself to eventually trigger another event. The system is said to be on the edge between order (no significant events) and chaos (unpredictability of events)

Recently economists have tried to find evidence in the dynamics of financial markets to suggest SOC response in the social behavior of markets. In this book we present data for the evolution of technical innovation that exhibits sudden exponential growth in measures of technical progress such as patents filed and market use of the technology. The construction of social network diagrams has associated with

it similar statistics regarding the growth of network nodes and links, namely the sudden exponential increase in the size of the network. It is tempting to suggest that technical innovation is a case of *self-organized criticality* in which the social network of contributors advance the technology.

One broad outline of such a theory imagines the social innovation network as a set of players in a technical innovation market. When some new technology comes along, such as the steam engine or internal combustion engine, players on the sideline with relevant knowledge or capital begin to come into the market by connecting with other players. We might assume that there is a reservoir of technical knowledge, generated from other innovations, that can at some point be transferred to the new technology. As the network grows through linkages, new players come into the network with new knowledge or capital that in turn stimulates more linkages with other players in the knowledge reservoir.

For example, by the time the Wright brothers came into the aviation network c. 1900, there were already several dozen significant nodes, including Lilienthal, Langley and Chanute. The internal combustion network was already in a critical state with hundreds of players, dozens of manufacturing firms and several thousand players associated with ballooning technology. We could argue that the Wright brothers were drawn into the early aviation network. And after the Wright brothers created their own flying machine of 1903, they in turn drew many more players into the aviation social network. [See Chap. 4 for details.]

In another example discussed in Chap. 3, by the time Henry Ford produced his first horseless carriage c. 1896, there were more than 500 patent applications in the US alone related to automotive technology. And when Ford produced his Model T , c. 1903, he induced hundreds more players to join the automotive innovation network.

The goal of this book is not to create a SOC theory for social innovation networks but to provide historical data in a statistical format that might suggest models for innovation based on the growth of historical social networks.

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